Software Development Plan for FAME Data Analysis and Reductions

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1 Steps in the Data Reduction Chain

Software development for the FAME data analysis and reductions must proceed in logical sequence. Many tasks must be completed and verified well before launch date while others will most likely be refined during the mission. Regardless of the time-frame, a general idea of the complexity and resources needed to complete each major step need to be known. The major steps include: first-look tasks; build-up of angles; z-axis attitude determination; great-circle reduction; sphere reconstruction and astrometric parameter determination; spectral fitting of color data; multiple star system processing; and data distribution.

1.1 First-Look and Troubleshooting

Purpose

Data gathered from the FAME satellite must be checked in near real-time to ensure that the hardware and software are working correctly. To do this, the data from the satellite need to be checked to ensure that images are detectable, are adequately visible, and coincide at least roughly with the input catalog. If any of these criteria are not met, then problems with the satellite or input data may be indicated.

Procedures

The following are the major steps needed to be coded for the first-look and troubleshooting analysis:

- Data must be evaluated for image detection.
- Envelope fitting must be performed.
- Images must be evaluated for visibility vs. input catalog data.

- Data from several stars' y-coordinates and transit times are combined to yield an estimated satellite attitude.
- Software must be in place to communicate with ground operations regarding possible clocking problems, attitude error, input catalog error, or satellite vibrations.

Image detection

The data from the scientific and TOF chips must first be analyzed to be sure that images are detected close to where the input catalog position indicates. Failure to detect images, which may result due to the "windowing" of the data from the arrays, should initialize additional data checks starting with evaluation on any light detection above background noise. If light is detected near the input star positions, then a possible clocking error (resulting in envelope being "smeared" across the detector) or satellite vibrations could be the cause. In this case, Ground Ops are to be notified of this possibility and the problem must be further investigated. If no light is detected, then an input catalog error or satellite attitude error may be the cause. Ground Ops are to be notified of this possibility and the problem must be further investigated.

Envelope fitting

The intensities in the x and y direction of the pixelized data are analyzed using a least-squares fit to yield peak in the image envelope. This, in addition to the clock data, are used in the determination of the time of transit and y-coordinate of the image.

Image visibility

Intensities of the images are evaluated against the input catalog data. If there is an unacceptable systematic decrease in the measured intensities with respect to the input catalog, Ground Ops are to be notified. Possible causes of inadequate image visibility are clocking errors or satellite vibrations.

Estimate of satellite attitude

The computed y-coordinates and time of transits of stars over a period of several minutes will be combined to compute the xy-plane as a function of time. The direction orthogonal to this plane is the time-varying axis of rotation, the z-direction. These parameters are to be continuously monitored by the software and unacceptable deviations from ideal are to be communicated to Ground Ops immediately.

1.2 Build-Up of Angles

Purpose

As the FAME satellite rotates, a swath of sky along a great-circle is scanned by the two fields of view. Timing of the *transits* of the star images multiplied by the rotation rate produces an angular separation between stars along the scan direction. This section details the steps needed to determine the along-scan angular separations of all stars within a great-circle scan.

Procedures

The following are the major steps needed to be coded for the Build-Up of angles section.

- Centroid envelope from both arrays.
- Check for multiplicity.
- Determine distance between scientific and TOF arrays
- Determine transit time of scientific array for all stars
- Determine transit time of TOF array for subset of stars
- Compute $\omega(t)$
- Compute array attitude
- Compute angular separation of all stars

Envelope fitting

The same basic software used to fit the envelope from the *First-look* procedures is used. It involves a least-squares fit to determine the peak in image envelope in both the x and y directions. Data from the clock is used to compute the time of transit of the image. Peak in intensity in the y-direction yields the y-coordinate of the star.

Checking for multiplicity

Stars previously known to be multiple but are separated adequately so no image interference is detected will be reduced as single images but noted. They will not be used for satellite attitude determination or for great-circle zero-point reductions because of probable accellerations of their space motion. All stars suspected of multiplicity due to an apparent super-imposition of envelopes or a large standard deviation from the least-squares envelope fitting software will be noted and treated separately.

Determining distances between arrays

Determining transit times

Clock resolution is on the order of 400 Megahertz. A time-stamp is attached to each CCD readout during the observation of a star. The expected precision of the centroiding of an envelope peak is about 15 μas, so the time-stamps from the CCD readouts are interpolated to the transit of envelope peak. This procedure is done for all transits of both scientific or TOF arrays.

Computing $\omega(t)$

The time-varying rotation rate, $\omega(t)$, will be determined by a least-squares polynomial fit to all rotation-rate determinations obtained from single stars crossing the TOF array. Each rotation rate determination is computed by dividing the angular separation between the scientific and TOF arrays by the measured time between image transits. Jet actuations introduce errors in along-scan attitude knowledge of about 10 μas/firing. Segments of the great-circle between jet firings will be tied together rigidly by virtue of the 50% overlap between adjacent scans and ensuring that the jets are not used at the same points along both scans.

Computing array attitude

Computing angular separation

The along-scan angular separation between an arbitrary zero point and star i is given by

$$\int_{t_0}^{t_i} \omega(t)dt \tag{1}$$

where $\omega(t)$ is the time-dependent rotational velocity, t_0 and t_i are the computed transit times of the zero point and the star, respectively. Angular separation of all stars along a great-circle scan are thus determined.

1.3 Z-Axis Attitude Determination

Purpose

The z-axis direction needs to be known precisely to minimize projection effects caused by minor fluctuations in the pole of the great-circle being scanned. Deviations higher than 100 μas will contribute significantly to the error budget. Attitude knowledge of this precision cannot be determined from the the onboard navigation systems, therefore data from the scientific package must be utilized. This section details the steps needed to determine the time-varying z-axis.

Procedures

The following are the major steps needed to be coded for the z-axis attitude determination. Note that this entire section is used as part of the *First-look* tasks.

- Position for a subset of stars are needed *a priori*
- Compute mean y-coordinate for each star
- Determine time-varying xy plane
- Compute z-axis as function of time

A priori position information

Initially, data from the input catalog will be loaded onto the spacecraft. Following preliminary FAME data reductions, updates to the input catalog will be utilized. This step is already coded in order to "window" the data being sent from the satellite to Ground Ops.

Computing x and y-coordinate

This step has already been performed as part of the Build-up of Angles section.

Compute $xy(t)$ plane

This is the same coding as in the first-look section.

Compute $z(t)$

This is the same coding as in the first-look section.

1.4 Great-circle Reductions

Purpose

The great-circle reductions are performed on a number of individual successive great-circle scans to minimize uncompensated scale changes and determine an origin. The scale changes may have arisen from errors in the angular velocity, attitude knowledge, or clock stability.

Procedure

The following are the major steps needed for the great-circle reduction section.

- Determine preliminary corrected scale, $\Omega(t)$, from 2π radian closure condition

- Apply harmonic analysis to determine $\Delta\Omega(t)$ using basic angle equations of constraint
- Solve for Fourier coefficients to determine $\Delta\Omega(t)$
- Determine great-circle zero point
- Apply corrected scale to individual abscissa

Determining average scale

The preliminary correction to the assumed scale of the instrument, in units of angle per unit time, is computed by the closure condition imposed at the completion of a great-circle scan. That is

$$E_c = 2\pi - \int_0^{\tau} \Omega(t) dt \tag{2}$$

where E_c is the preliminary correction to the assumed scale Ω, and τ is the time it takes to scan 2π radians. The preliminarily corrected scale value is now

$$\Omega(t) \rightarrow \Omega(t) - E_c/\tau. \tag{3}$$

Determine deviations from preliminary corrected scale

The deviations from the preliminary corrected scale function, $\Omega(t)$, are determined by harmonic analysis whose Fourier coefficients are determined by constraints imposed by basic angle scans. The equations of constraint imposed by the i^{th} basic-angle scan may be written as

$$\int_{t_i}^{t_i+\tau_i} [\Omega_{true}(t) - \Omega(t)] dt = \Delta_i \tag{4}$$

where τ_i is the time required to complete the i^{th} basic-angle scan, Δ_i is the empirical disagreement between the known basic-angle and the scale integrated over the i^{th} interval. In this expression, $[\Omega_{true}(t) - \Omega(t)]$ may be expanded in a Fourier series and integrated term by term. If an equation of the form of Eq. 4 is set up for each of M basic-angle scans, the constraints are summarized in matrix notation:

$$\mathbf{FA} = \mathbf{\Delta} \tag{5}$$

where $\mathbf{F}$ is the matrix of sines and cosines integrated over the M intervals, $\mathbf{A}$ is a column matrix of Fourier coefficients and $\mathbf{\Delta}$ is a column matrix of the empirical basic-angle scan errors. All of the scan errors are used to compute each Fourier coefficient:

$$A_j = \sum_{k=i}^{M} \Delta_k {F_{jk}}^{-1} \tag{6}$$

where $F_{jk}^{-}1$ is the (j,k) component of the matrix inverse of $\mathbf{F}$.

Determination of great-circle zero-point

Application of new scale value to abscissae

The revised along-scan angular separation between the zero-point and star i is now given by

$$\int_{t_0}^{t_i} \Omega(t) dt \tag{7}$$

1.5 Sphere Reconstruction and Astrometric Parameter Determination

Purpose

Each great-circle scan defines an independent system. In the sphere reconstruction step, these systems are all brought together to form a single, global system, removing all arbitrary rotations found in the great-circle reductions. This will be achieved by solving for the great-circle origins and the astrometric parameters of the majority of stars using the abscissae from the great-circle reductions. It is important to use only stars whose space-velocities are constant; stars suspected of multiplicity must be avoided and treated separately.

Procedure

After the great-circle reductions, the FAME data analysis is very similar to that of the Hipparcos mission. The FAME data reduction team has decided to use the procedure developed at Hipparcos's Northern Data Analysis Consortium (NDAC). The following are the major steps needed to be coded for the Sphere Reconstruction and Astrometric Parameter Determination section.

- Gather and compute needed input data.
- Model abscissa as independent random variable.
- Build-up system of observation equations.
- Form system of normal equations.
- Adjust and eliminate astrometric parameters from normal equations
- Solve for global parameters and great-circle origin corrections
- Iterate until convergence.

Input data

Input to the sphere reconstruction stage is *a priori* astrometric data, abscissa data from the great-circle reductions, and a few other computed parameters and constants. The astrometric data needed are the $\alpha, \delta, \mu_\alpha, \mu_\delta$, parallax Π, radial velocity V, color index CI and epoch for each star. These data will come from the input catalog or its updated version Some of these data, in particular the proper motions, parallaxes and radial velocities, initially may be unknown and set to zero. The abscissa data will contain the mean time of reference great-circle epoch, the α, δ of the reference great-circle pole, the individual abscissae, and the standard error of each abscissa. Additional data needed are the speed of light, the astronomical unit, and the computed barycentric position and velocity of the Earth at the mean time of reference great-circle epoch.

Abscissa as independent random variable

In this stage, the observed abscissa are modeled as an independent Gaussian random variable with expectation

$$E(\nu_{ij}) = \nu(T_j, \alpha_j, \delta_j, T_i, \alpha_i, \delta_i, \Pi_i, \mu_{\alpha i}, \mu_{\delta i}, V_i) - c_j + g\prime_{ji}, \ + n_{ji} s_g \tag{8}$$

The function ν is found in Eqs. 9.2 and 9.3 on pg. 173 of SP-1111 vol.3. The number i represents an individual abscissa and j represents the reference great-circle number. In Eq. 8, c_j is the zero-point correction of the j^{th} reference great-circle and , is a vector of global unknowns. In the Hipparcos reductions, the coefficients of , represent periodic basic-angle vibrations, corrections due to gravitational light deflection formulas, corrections due to aberration and corrections due to chromacity (see Eqs. 9.4 through 9.7, p. 173 SP-1111 vol. 3). In the FAME reductions, these and other yet to be identified global unknowns will most likely need to be solved. Although not all global parameters are currently known, the procedure for the sphere solution and astrometric parameter determination remains the same.

Observation equations and solution

The input data is used create a system of unit-weight observation equations as shown in the matrix notation of Eq. 9.8 p. 175 SP-1111 vol. 3. From this system, normal equations of the form shown in Eq. 9.13 can be developed. The astrometric parameters are adjusted for each star one at a time, then eliminated from the equations as if the values from c and , are correct. The entire process is iterated until the corrections to c and , converge to zero. At this point, the astrometric parameters have also converged.

1.6 Spectral Fitting of Color Data

Purpose

Procedure

1.7 Multiple Star System Processing

Purpose

Procedure

1.8 Fast Moving Objects

Purpose

Procedure

1.9 Input Catalog Preparation

Purpose

Procedure

1.10 Data Distribution

Purpose

Data needs to get to the Science team and, eventually, the public in an easy, efficient manner. Current modes of transferring data, which this section details, may be antiquated by the time of the FAME mission.

Procedure

The following items are needed to ensure efficient data distribution.

- Database developed to be accessed over the World Wide Web
- Procedures in place to get catalog to the international data centers

Database access

Currently, file transfer protocol (FTP) over the World Wide Web (WWW) is one of the quickest and easiest method of transferring data. Programs such as Mosaic use hyper-text links so users can easily get to areas of inquiry for their specific needs. The FAME database will be designed to be accessed on the WWW via Mosaic and contain a Graphical User Interface (GUI) driven menu to facilitate easy data distribution. Originally the data will be available only to specific users (the Science team, for instance) so safeguards will need to be in place to deny unauthorized access. Following public release, parts of the database will be accessible to all via Mosaic and the WWW. The final astrometric and color catalog will be available by anonymous FTP from the USNO as well as by the National Space Science Data Center and Centre de Donnees Astronomique de Strasbourg.

Final catalog to data centers

The final data will be placed in the National Space Science Data Center (NSSDC) in the USA and the Centre de Donnees Astronomique de Strasbourg (CDS) in Europe. These data centers have strict rules of preparing the description and data prior to submission. The USNO has submitted several data sets to these data centers and the rules and regulations are well-known.

2 Database Development and Management

Developing and managing the database to handle the expected 1-terabyte of data from the FAME mission will be an exceptionally important task. Some of the requirements of the database will be to: work with the data coming into the Deep-Space Network and Goddard; handle all needed data; be easy to use and access; have adequate speed; contain safety features ensuring against corruption and unauthorized access.

2.1 Communications with DSN and Goddard

2.2 Inclusion of Data

2.3 Speed Requirements

2.4 Ease of Access

2.5 Safety Features

3 Scheduling

Due to the time schedule of the MIDEX objectives and funding, strict adherence to the time-frame outlined in this section is required.

3.1 Software Development and Testing

First-look and troubleshooting

Coding for this section will start immediately following award of the proposal. All coding must be written and tested no later than one full year prior to launch, giving the Software development team two years to complete this task.

Build-up of angles

Coding for this section will start immediately following award of the proposal. All coding must be written and tested no later than six-months prior to launch, giving the Software development team 2.5 years to complete this task.

Z-axis attitude determination

All coding in this section is included in the *First-look* section. No new coding will be needed.

Great-circle reductions

Modeling for this section will start immediately following award of the proposal. Complete coding will follow immediately after the best model is selected. All coding must be written and tested no later than six-months prior to launch.

Sphere reconstruction and astrometric parameter determination

Modeling for this section will start immediately following award of the proposal. Complete coding will follow after the best model is selected. It may be necessary to change the coding in a non-trivial way based on the hardware of the satellite, due to the global parameters to be solved. This coding should be written and tested prior to launch.

3.2 Database Development and Management

Development of the FAME database will start immediately following award of the proposal. It is anticipated that most of the development will be completed within 2 years, allowing 1 year for minor revisions and testing its compatibility with the reduction software. Database management will be an on-going task beginning of the first day of flight and lasting at least one year following completion of the mission.

3.3 Astrometric Reductions

First-look reductions

Astrometric reductions, in the form of *First-look tasks* will be completed in real-time as the data become available from the Deep Space Network. This is an obvious necessity to ensure the satellite and software are working properly.

Through great-circle reductions

All tasks up to and including the *great-circle reductions* will be performed within two weeks of observation.

Sphere reconstruction and astrometric parameter determination

This step of the reduction chain can only be done following several hundred individual *great-circle reductions* are completed. Current plans are to apply this step only after 6 months of data are accumulated. It is planned that this step will be performed at intervals of every six months. The results will be introduced back into the reduction chain as updates to the input catalog.

3.4 Data Distribution

Release to the science team

It is anticipated that the preliminary astrometric and color data will be available to the co-investigators and other members of the science team within 18 after launch. Data will be available by computer account at USNO. Subsequent releases will be made to the science team at 6 month intervals. After completion of the final catalog, the science team will have exclusive rights for one year to complete their investigations into the cosmic distance scale, stellar evolutionary models, and galactic kinematics.

Release to the general public

The general public will have access to the final catalog of positions, proper motions, distances and colors one year after final reductions. It is anticipated that this will be 18 months following termination of the mission. The data will be available on the WWW as well as at the National Space Science Data Center (NSSDC) and the Centre de Donnees Astronomique de Strasbourg (CDS).